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J. Strait et. al

Fermi National Accelerator Laboratory
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TEVATRON ENERGY AND LUMINOSITY UPGRADES BEYOND THE MAIN INJECTOR

D. AMIDEI[c], A. BADEN[b], G. W. FOSTER[a], G.P. JACKSON[a], T. KAMON[d], J. LOPEZ[d], P. MCINTYRE[d], J. STRAIT*[a], and J. WHITE[d]

[a]*Fermi National Accelerator Laboratory*

[b]*Department of Physics, University of Maryland*

[c]*Department of Physics, University of Michigan*

[d]*Department of Physics, Texas A&M University*

ABSTRACT

The Fermilab Tevatron will be the world's highest energy hadron collider until the LHC is commissioned, it has the world's highest energy fixed target beams, and Fermilab will be the leading high energy physics laboratory in the US for the foreseeable future. Following the demise of the SSC, a number of possible upgrades to the Tevatron complex, beyond construction of the Main Injector, are being discussed. Using existing technology, it appears possible to increase the luminosity of the $\bar{p}p$ Collider to at least $10^{33}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ (TevatronStar) and to increase the beam energy to 2 TeV (DiTevatron). Fixed target beam of energy about 1.5 TeV could also be delivered. Leaving the existing Tevatron in the tunnel and constructing bypasses around the collider halls would allow simultaneous 800 GeV fixed target and $\sqrt{s} = 4$ TeV collider operation. These upgrades would give Fermilab an exciting physics program which would be complementary to the LHC, and they would lay the groundwork for the construction of a possible post-LHC ultra-high energy hadron collider.

1. Introduction

Ideas for upgrading the energy and luminosity of the Tevatron beyond that planned with the Main Injector are not new.[1] However, the cancellation of the SSC has given new impetus to developing and implementing these ideas. Fermilab is the US flagship HEP lab, and if there is to be a future for hadron physics in the US, it will be centered at Fermilab. Continued development and enhancement of its facilities and physics research program are necessary to maintain its long term vitality. For the last decade hadron accelerator physics has been concentrated on a single large construction project, the SSC. As a result, a number of promising R&D projects have been left at the wayside. With the SSC gone, it is now appropriate to resume efforts on a mixture of long-term research pointing toward far-future facilities and short-term development of the capabilities of the existing facilities.

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*Presenting Author

There is important physics research which an upgraded Tevatron can address. A $\sqrt{s} = 4$ TeV, $\mathcal{L} = 10^{33}/\mathrm{cm}^2/\mathrm{s}$ $\bar{p}p$ collider is a "Top Factory," producing up to 1000 reconstructed $t\bar{t}$ pairs per week. The sensitivity to detect an intermediate mass Higgs (80~120 GeV) via WH associated production with $H \to b\bar{b}$ is comparable to that of LHC.[2] Most of the parameter space of a set of well motivated constrained SUSY models can be covered: gluino mass up to 750 (450) GeV/c^2 at $\sqrt{s} = 4$ (2) TeV and chargino mass up to 150–200 GeV/c^2 for either energy.[3] An energy upgrade is effectively a luminosity upgrade for fixed target physics. Doubling the primary beam energy increases the flux of secondary beams by up to an order of magnitude. Some upgrade scenarios involve leaving the existing Tevatron in the tunnel, which would allow 800 GeV fixed target running simultaneously with 2+2 TeV collider operation. Charm, hyperon, and neutrino physics would be enhanced. For example, experiments with more than 10^8 reconstructed charmed mesons are possible.

Physics done by the LHC and a $\mathcal{L} = 10^{33}/\mathrm{cm}^2/\mathrm{s}$, $\sqrt{s} = 4$ TeV $\bar{p}p$ collider are complementary. In the few hundred GeV mass range, where we expect there to be new phenomena, a $\sqrt{s} = 14$ TeV pp collider is dominantly a gg collider and a $\sqrt{s} = 2$-4 TeV $\bar{p}p$ collider is dominantly a $q\bar{q}$ collider.[4] For processes such as WH associated production and $t\bar{b}$ production, which proceed dominantly from a $q\bar{q}$ initial state and for which the dominant background comes from gg interactions, the signal to background ratio will be better in a $\bar{p}p$ than a pp collider. If LHC concentrates on Higgs research to the highest possible mass (or in the intermediate mass range in the $H \to \gamma\gamma$ mode), it must run at the highest possible luminosity and therefore with at least 15 interactions/crossing. With the DiTevatron operating such that there are only a few interactions per crossing, physics that relies on b-tagging and good missing E_T resolution can be done with greater efficiency. Fixed target beams up to ~1.5 TeV will allow physics to be done that cannot be done at LHC (or elsewhere); e.g. ultra-high statistics charm physics, perhaps leading to the observation of $D^0\overline{D}{}^0$ mixing and maybe even CP violation.

The LHC is unlikely to answer all the questions we know to ask now, nor does it represent the limit of hadron collider technology. Therefore, we will want to build an ultra-high energy ($\geq$ 30+30 TeV) hadron collider after LHC. One lesson of the SSC is that we should build incrementally on existing facilities, rather than starting a new lab when we need a new accelerator, and a 2 TeV rapid cycling accelerator would be an appropriate injector for the post-LHC machine. The accelerator R&D required for the energy and luminosity upgrades of the Tevatron, for example the development of antiproton source technology or the generation and acceleration of high-brightness proton beams, could help us learn how to build future machines more economically.

Two potential upgrades are being considered, which may be implemented separately or together. The first, Tevatron-Star (TeV*), is an increase in the collider luminosity to $\mathcal{L} = 10^{33}/\mathrm{cm}^2/\mathrm{s}$ (10 fb^{-1}/yr), an order of magnitude above that with the Main Injector. The principal project is to upgrade the $\bar{p}$ source to increase $\bar{p}$ production by a factor of 6 and to recycle the remaining $\bar{p}$'s at the end of a store. Improvements to the injector chain would also be needed to produce a brighter proton beam. The second, the DiTevatron, uses SSC magnet technology to double the Tevatron energy to 2 TeV per beam. Adiabatic damping of the beam size would give a natural $\times 2$ increase in luminosity over the Tevatron to $\mathcal{L} = 2\times10^{32}/\mathrm{cm}^2/\mathrm{s}$ (2 fb^{-1}/yr) without the TeV* upgrade and $\mathcal{L} = 2\times10^{33}/\mathrm{cm}^2/\mathrm{s}$ (20 $\mathrm{fb}^{-1}/\mathrm{yr}$) with it.

2. Tevatron-Star

Currently, one Booster batch (84 bunches) in the Main Ring (and later the Main Injector) is targeted for $\bar{p}$ production. Antiprotons are collected with a 4% momentum bite and cooled and stored in 2 rings – the Debuncher and Accumulator – which operate at the same energy (8 GeV) and have a similar circumference as the Booster. At the end of a store the remaining $\bar{p}$'s in the Tevatron, about 30% of the initial number, are dumped. With the Main Ring, the stacking rate is 4×10^{10}/hour and with the Main Injector it is expected to increase to 15×10^{10}/hour. If the $\bar{p}$'s remaining at the end of the store can be re-used and a factor of 6 higher stacking rate is obtained, then an order of magnitude luminosity increase will be realized.

The "simplest" method to increase the $\bar{p}$ production rate is to target 6 Booster batches (the capacity of the Main Injector allowing for kicker gaps) rather than one. This requires the construction of a new ring, the Compressor, which has the same circumference as the Main Injector and which would be placed in the same tunnel. Bunch rotation would be performed in the new ring, and then the 6 Booster batches worth of $\bar{p}$'s would be compressed azimuthally and transferred to the existing Antiproton Source for cooling and accumulation. A second new ring, the Recycler, is required to store the stack of at least 1.3×10^{13}, which substantially exceeds the capacity of the existing Accumulator. The Recycler would have only a core cooling system and would operate above the Main Injector transition energy. It would also be used to accept and recool the $\bar{p}$'s remaining in the Tevatron at the end of the store. The Recycler could be located in either the Main Injector or Antiproton Source tunnel.

Table 1 compares several possible luminosity and energy upgrade scenarios. In all cases the following parameters are assumed: β^*=25 cm, recovered $\bar{p}$ fraction = 30%, $\bar{p}$ transfer efficiency = 80%, coalescing efficiency = 75%, and stacking time between stores = 13 hours. The first column gives the expected performance with the Main Injector. For 1(2) TeV beam and 36 bunches, $\mathcal{L} = 1.2(2.4)\times10^{32}/\mathrm{cm}^2/\mathrm{s}$ and there will be about 3(6) interactions per crossing. If the luminosity is increased ten-fold, the number of interactions per crossing would become unacceptably large. The second column (TeV* A) is the case in which the number of bunches is increased to 108 and the spacing is reduced to 132 ns. The collider detector electronics are currently being upgraded to accommodate this bunch spacing. It is assumed that modest improvements in the injector chain, either improved operation of the existing accelerators or accelerator upgrades, will result in a 40% decrease in the proton beam emittance and a 60% increase in the number of protons per RF bucket, from 40×10^9 to 64×10^9. With these parameters the desired $1(2)\times10^{33}$ luminosity is realized at 1(2) TeV per beam, and there will be 9(17) interactions per crossing.

The case TeV* B uses uncoalesced beams to decrease the number of interactions per crossing. Due to the smaller momentum spread of the uncoalesced beam, the bunch length decreases, giving an increase in the "hour glass" form factor. However, a non-zero crossing angle, such that the beams are separated by 5σ at the next crossing point reduces the overall form factor. With lower density bunches, the luminosity is now about 1/3 of the desired value. The last column (TeV* C) assumes that the emittances

Table 1. Tevatron Upgrade Scenarios

	Main Injector	TeV* A	TeV* B	TeV* C
$\bar{p}$ Production Rate (10^{10}/hour)	15	90	90	90
E_{beam} (TeV)	1(2)	1(2)	1(2)	1(2)
Number Coalesced	13	5	1	1
Number of Bunches	36	108	750	750
Bunch Spacing (ns)	395	132	19	19
N_p/bunch (10^9)	390	240	64	64
$N_{\bar{p}}$/bunch (10^9)	33	93	18	18
ϵ_p (rms, πmm mrad)	5	3	3	1
$\epsilon_{\bar{p}}$ (rms, πmm mrad)	2.5	2.5	2.5	1
rms Bunch Length (cm)	45	30	10	8
Crossing Half Angle (mrad)	0	0	0.27	0.15
Luminosity Form Factor	0.6	0.7	0.64	0.77
Peak $\mathcal{L}$ 10^{32}/cm^2/s	1.2(2.9)	10(20)	3(6)	11(21)
Integrated $\mathcal{L}$ (pb^{-1}/week)	24(48)	200(400)	65(130)	220(430)
Interactions/crossing (45 mb)	3.1(6.2)	9(17)	0.4(0.8)	1.3(2.7)
p Tune Shift	0.003	0.009	0.002	0.004
$\bar{p}$ Tune Shift	0.019	0.020	0.005	0.016

can be reduced to 1 π mm-mrad by appropriate accelerator improvements. This is the most desirable case: $\mathcal{L}$ =1-2$\times 10^{33}$/cm^2/s, and 1-3 interactions per crossing.

There are many technical issues that must be addressed to reach the parameters of the TeV* C case. To use 6 Booster batches without destroying the target requires a more advanced beam sweeping system (hard), defocussing the beam (reduced $\bar{p}$ production efficiency) or use of multiple target stations (expensive). Bunch rotation in the Compressor is done most easily near transition, or at ~15 GeV. This requires deceleration either in the Compressor (complicates the Compressor design) or the Main Injector (increased cycle time). Pre-cooling in the large circumference Compressor ring requires impractically large power, and to cool the larger $\bar{p}$ flux, the Accumulator cooling system bandwidth would have to be increased by a factor of eight. To generate the very low emittance beams probably requires replacing the present source with an RFQ, and preserving the low emittance through all of the accelerators will be challenging.

The very small beams required for high luminosity with uncoalesced beam may have unacceptably short emittance growth times due to intra-beam scattering. Experiments are planned at Fermilab to measure this effect. The large number of long-range ("parasitic") beam-beam collisions (1500) may give rise to unacceptable tune spread and tune shift. The use of small, low emittance beams tends to mitigate this problem since the tune shift and tune spread are proportional to $(D/\sigma)^{-2}$ and $(D/\sigma)^{-3.8}$ respectively,[5] where σ is the rms beam size and D is the beam separation. (The achievable values of D/σ will be discussed further below.) This effect can be studied in the Tevatron by injecting a bunch of $\bar{p}$'s along with a fixed-target proton beam.

3. DiTevatron

Upgrading the beam energy to 2 TeV requires the construction of a new accelerator with magnets twice the strength of Tevatron magnets. Assuming the same lattice as the Tevatron, dipoles of 8.8 T and arc quadrupoles of 150 T/m are required. Preliminary designs exist in which the IR quadrupole gradient would only be increased to 210 T/m. All of these magnet strengths are achievable using technology developed for the SSC. The energy upgrade could be implemented alone or together with the luminosity upgrade discussed above.

Two main variants of this proposal under discussion: 1) Remove the Tevatron and inject into the DiTevatron directly from the Main Injector. High energy fixed target beams would be available only when the collider was not running and 120 GeV fixed target beam would be available during collider runs only if the luminosity upgrade does not require the full Main Injector beam. 2) Leave the Tevatron in the tunnel (or reassemble it above the DiTevatron) and use it as a high energy injector. If bypasses were built around the collider experiments, 800 GeV fixed target beams could be delivered during a collider run. This would also allow the possibility, not considered further here, of 1+2 TeV pp collisions. However, the expense of operating two superconducting accelerators would be substantial.

The Tevatron collider runs about 5% below the point where the weakest magnet quenches. Therefore, DiTevatron magnets must reach 9.2 T to allow reliable 2 TeV collider operation. The SSC dipoles provide a "proof of principle" that the required field strength can be achieved. Twenty full-scale SSC dipoles built at Fermilab and BNL routinely reached 7.2 T at 4.35 K and 8 T at 3.5 K.[6] One magnet was tested at Fermilab at 1.8 K; it reached 9.4 T on the first quench and 9.6 T after 5 quenches.[7]

Tevatron dipoles, which have a coil inner diameter of 76 mm, have a "good field region" (over which $\delta B/B_0 \leq 10^{-4}$) of about 50 mm diameter. SSC dipoles have a 50 mm aperture, and the early models had only a 15 mm good field region.[8] With minor modifications to the design this could be increased to about 35 mm, which may be large enough to accommodate the smaller beams associated with the luminosity upgrade.

The largest aperture for collider operation is required at injection. In current 6 bunch operation the beams are separated from each other by $5\sigma \cong 15$ mm. If both beams are to be $\geq 5\sigma$ from the edge of the good field region, a good field aperture ≥ 45 mm is required, just less than that in the Tevatron magnets and larger than can be achieved with SSC dipoles. Table 2 compares the beam size at 150 GeV in the Tevatron with those for the upgrade configurations given in Table 1. Lattices have been worked out for an energy upgrade that have smaller maximum dispersion than the Tevatron.[9] This assumed in the last 4 columns. The value of D/σ in the last row results from putting the beams 5σ from the edge of the 50 (35) mm good field region in the Tevatron (DiTevatron). In the case TeV* C, the possible separation is $> 30\ \sigma$, which may be sufficient to keep the parasitic beam-beam effects under control.

The existing refrigeration system has the capacity at 4.5 K to remove heat from the Tevatron due to the sum of the cryostat and power lead heat leaks plus AC losses

Table 2. DiTevatron Beam Sizes

	Tevatron	DiTevatron			
	Main Injector	Main Injector	TeV* A	TeV* B	TeV* C
ϵ_p (rms, πmm mrad)	5	5	3	3	1
$\epsilon_{\bar{p}}$ (rms, πmm mrad)	2.5	2.5	2.5	2.5	1
$\sigma_p/p(10^{-4})$	5	5	2.4	0.9	0.9
Dispersion (m)	5	3.6	3.6	3.6	3.6
σ_{xp} (mm)	3.1	2.5	1.6	1.4	0.9
$\sigma_{x\bar{p}}$ (mm)	2.8	2.2	1.5	1.3	0.9
D/σ_{xp}	6	4	12	15	31

during fixed target running. DiTevatron magnets would have a much more efficient cryostat, but would operate at 1.8 K. The greater cost of removing heat from 1.8 K than 4.5 K (×6) would roughly cancel the lower heat leak of the DiTevatron, so the capacity of the existing refrigeration system would be adequate for the DiTevatron as a collider.[10] However, AC losses for fixed target operation would be substantially larger than for the Tevatron due to the larger energy swing, the larger volume of superconductor, and eddy current losses in the cold iron yoke. The lower refrigeration efficiency at 1.8 K would make 2 TeV fixed target operation an order of magnitude more expensive than current 800 GeV running and would require a correspondingly larger refrigerator. Thus 2 TeV fixed target operation seems impractical.

Allowing a 15% quench margin, as with the Tevatron in fixed target mode, the DiTevatron could operate to 1.4 (1.6) TeV at 4.4 (3.5) K. The AC losses for 1.5 TeV are only about 70% as large as for 2 TeV, and the refrigeration efficiency is larger at higher temperature. Also, the limited length of the straight sections in the existing tunnel (50 m) makes extraction at 2 TeV much more difficult than at 1.5 TeV.[11] Thus 1.4–1.6 TeV appears to be the practical limit for fixed target beam from the DiTevatron.

For secondary fixed target beams, an energy increase of the primary beam is effectively a luminosity increase. An alternate way to deliver more integrated luminosity would be to leave the Tevatron in the tunnel, build bypasses around the collider experiments, and operate the 800 GeV fixed target program a larger fraction of the time than is now possible. It is desirable that the bypasses be in the same plane as the Tevatron. Using SSC-strength magnets, operated at 4.4 K with a 15% margin, a bypass that separates the Tevatron and DiTevatron beams by 10 m at the collision points would occupy about 7% of the circumference of the Tevatron and require about thirty 12 m long dipoles per interaction region.

4. Conclusions

The energy and luminosity upgrades to the Fermilab accelerator complex discussed in this paper can be achieved with existing technology, although the state-of-the-art will be pushed in some cases. There are strong reasons, both for physics and for the health of the US HEP program, to invest in Fermilab beyond the Main Injector:

Important physics, which is complementary to the LHC, can be done with a $\sqrt{s}$ = 4 TeV, $\mathcal{L}$ =$2\times 10^{33}/\mathrm{cm}^2/\mathrm{s}$ $\bar{p}p$ collider and with enhanced fixed target beams (1.5 TeV between collider runs or 800 GeV "full time"). An upgraded accelerator complex at Fermilab would be a first-rate injector into a possible post LHC ultra-high energy hadron collider. And the investment in accelerator R&D could lead to new developments that could make such an ultra-high energy collider less expensive to build. Further study will continue to develop these ideas and plans.

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